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SO_x-NO_x-Rox Box™
Flue Gas Cleanup Demonstration

A DOE Assessment

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Executive Summary

This document serves as a U.S. Department of Energy (DOE) post-project assessment of a project in Clean Coal Technology (CCT) Round 2, the SO_x-NO_x-Rox Box™ Flue Gas Cleanup Demonstration Project. In December 1989, The Babcock and Wilcox (B&W) Company entered into an agreement to conduct this study, with Ohio Edison as the host and cosponsor. Additional funding was provided by the Electric Power Research Institute and the Ohio Coal Development Office. In-kind contributions were provided by Minnesota Mining and Manufacturing Company, Norton Company, and Owens-Corning Fiberglas Corporation. DOE provided 45.8% of the total project funding of $13.3 million. The demonstration was conducted between May 1992 and April 1993.

The SO_x-NO_x-Rox Box™ (SNRB™) process, developed by B&W, combines the removal of SO_2, NO_x, and particulates in one unit, a high temperature baghouse. SO_2 removal is accomplished by injecting either calcium- or sodium-based sorbents into the flue gas. NO_x removal is accomplished by selective catalytic reduction (SCR), using ammonia as the reagent. Particulate removal is accomplished with high-temperature fiber bag filters. A unique feature of the SNRB™ process is that all of the pollution removal functions take place within a single processing unit, with the SCR catalyst contained in the dirty side of the bags in the baghouse.

The performance objectives of this project were as follows:

- To demonstrate SO_2 removal efficiency of greater than 70% using a calcium-based sorbent, and greater than 90% using a sodium-based sorbent.

- To demonstrate NO_x removal efficiency of greater than 90% with minimal ammonia slip.

- To achieve particulate emissions below 0.03 $lb/10^6$ Btu.

All of these goals were met or exceeded during the demonstration, which was conducted at Ohio Edison's R.E. Burger Plant in Dilles Bottom, Ohio. Flue gas feed to the SNRB™ demonstration unit was a slipstream equivalent to 5 MWe of electric power. This boiler was fired with Midwestern bituminous coal having an average sulfur content of 3-4%.

SO_2 removal efficiencies greater than 80% were achieved with injection of commercially hydrated lime at a Ca/S molar ratio between 1.8 and 2.0. Alternative calcium-based sorbents gave improved SO_2 removal at similar Ca/S ratios. With sodium bicarbonate injection, SO_2 removal was greater than 90%.

NO_x removals greater than 90% with ammonia slip less than 5 ppm were realized over a broad range of catalyst temperatures. Particulate emissions downstream of the baghouse were less than 0.03 $lb/10^6$ Btu, representing an average collection efficiency of 99.9%.

Economics have been developed for a retrofit SNRB™ unit with 85% reduction in SO_2 emissions, 90% reduction in NO_x emissions, and all costs were estimated in 1994 dollars. At a power plant capacity of 150 MWe, the estimated capital cost is $253/kW. For a 15-year project life, the levelized

cost on a current dollar basis is 15.8 mills/kWh. This is equivalent to $721/ton of $SO_2 + NO_x$ removed. On a constant dollar basis, the levelized cost is 12.1 mills/kWh, equivalent to $553/ton removed. These costs are significantly lower than those for a conventional system consisting of separate units for SO_2, NO_x, and particulates removal. The SNRB^{TM} system offers operating flexibility, control of multiple pollutants, and low space requirements.

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I   Introduction

The goal of the U.S. Department of Energy (DOE) Clean Coal Technology (CCT) program is to furnish the energy marketplace with a number of advanced, more efficient, and environmentally responsible coal utilization technologies through demonstration projects. These projects seek to establish the commercial feasibility of the most promising advanced coal technologies that have developed beyond the proof-of-concept stage.

This document serves as a DOE post-project assessment of a project selected in CCT Round 2, "SO_x-NO_x-Rox Box™ Flue Gas Cleanup Demonstration Project," as described in a Report to Congress [1]. In December 1989, The Babcock and Wilcox (B&W) Company entered into a cooperative agreement to conduct the study. Ohio Edison was the host and cosponsor, with additional cofunding provided by the Electric Power Research Institute (EPRI) and the Ohio Coal Development Office. In-kind contributions were provided by Minnesota Mining and Manufacturing Company (3M), Norton Company, and Owens-Corning Fiberglas Corporation. DOE provided 45.8% of the total project funding of $13.3 million.

The demonstration was started in May 1992 and was completed in April 1993. The independent evaluation contained herein is based primarily on information from B&W's Final Report, dated September 1995 [6], as well as other references cited.

The SO_x-NO_x-Rox Box™ (SNRB™) process accomplishes removal of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulates in a single unit, a high-temperature baghouse. Flue gas desulfurization (FGD) for SO_2 removal is achieved by sorbent injection, and NO_x removal is achieved by selective catalytic reduction (SCR), using ammonia as the reagent. High-temperature fiber bag filters provide particulate removal. The combination of these functions in a single piece of equipment is a unique feature of the SNRB™ process.

The Clean Air Act, enacted in 1970, established New Source Performance Standards (NSPS) for emissions of SO_2, NO_x, and particulates, among other pollutants, from stationary coal-fired power plants. These regulations were made more stringent in the Clean Air Act Amendments (CAAA) of 1990.

The host site chosen for this CCT demonstration project was Ohio Edison's R.E. Burger Plant, located along the Ohio River in Dilles Bottom, Ohio. There are eight coal-fired boilers supplying five generating units at the plant. All of the boilers fire bituminous coal from Ohio and northern Appalachia. Flue gas feed to the SNRB™ demonstration unit was a 5-MWe equivalent slipstream from generating Unit No. 5, supplied by Boiler No. 8. Boiler No. 8 was built in 1955, before implementation of NSPS for pollution control from boilers. It is a 156-MWe B&W pulverized coal-fired drum-type boiler (RB-208), equipped with an electrostatic precipitator (ESP).

The performance objectives of this project were as follows:

- To demonstrate SO_2 removal efficiency of $\geq$ 70% using a calcium-based sorbent and $\geq$ 90% using a sodium-based sorbent.

- To demonstrate NO_x removal efficiency of $\geq$ 90% with minimal ammonia slip.

- To maintain particulate emissions below the NSPS level of 0.03 lb/10^6 Btu.

II   Technical and Environmental Assessment

A.   Promise of the Technology

This project was undertaken to evaluate the technical and economic feasibility of using SNRB^{TM} to reduce emissions of SO_2, NO_x, and particulates from coal-fired boilers in a single unit operation. This represents a unique approach compared with the use of three separate systems for SO_2, NO_x, and particulate removal. This demonstration was supported by the results of previous B&W studies.

The process involves the use of a high-temperature baghouse between the economizer and the combustion air heater. An advantage of this approach is a reduction in equipment and space requirements for the emissions control system. Since particulate and SO_2 removals occur upstream of the air heater, fouling and corrosion potential resulting from the presence of acid gases are substantially reduced, allowing the air heater to operate at lower flue gas outlet temperatures. A further advantage is the potential of enhanced energy recovery, which would result in improved boiler cycle efficiency compared to a system without SO_2 control. If this feature were verified, SNRB^{TM} would be one of the few SO_2/NO_x removal technologies that offers a reduction in parasitic power losses.

Development of the SNRB^{TM} process at B&W began with pilot testing of high-temperature dry sorbent injection for SO_2 in the 1960s, followed by integration of NO_x reduction in the 1970s and evaluation of various SCR catalysts and SO_2 sorbents in the 1980s. This early development work led to the issuance of several U.S. process patents to B&W, the most recent of which are Nos. 5,540,897; 5,567,394; and 5,585,081.

Continued development work, sponsored in part by the Ohio Coal Development Office, brought the process to the point where a larger scale demonstration was warranted. Although studies had been conducted to evaluate integrating the catalyst with the baghouse, actual performance in a commercial size hot baghouse was still required.

B.   Process Description

The SNRB^{TM} process combines the removal of SO_2, NO_x, and particulates in a single unit, a high-temperature baghouse (Figure 1). SO_2 removal is accomplished using either a calcium- or sodium-based sorbent injected into the flue gas. NO_x removal is accomplished by reaction with ammonia (NH_3) over a nonpromoted SCR catalyst, and particulate removal is achieved using a pulse-jet baghouse. In the demonstration project, the SCR catalyst was a zeolitic material, identified as NC-300^{TM}, provided by the Norton Chemical Process Products Company.

A schematic flowsheet showing the SNRB^{TM} process incorporated into the steam cycle of a coal-fired boiler is given in Figure 2. The economizer section, which is usually the last water-cooled heat transfer surface in the boiler, is used to heat the boiler feed water. The air heater recovers heat from the flue gas, increasing the temperature of the primary and secondary combustion air. In some retrofit
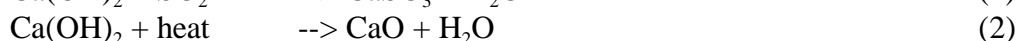
applications, modification of the heat transfer surfaces in the economizer and air heater may be necessary to optimize overall plant efficiency and emission control performance.

The three simultaneous emission control processes are discussed in the following sections.
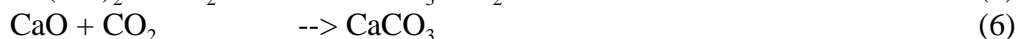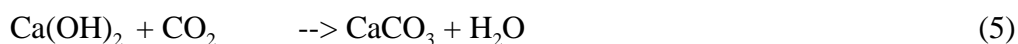
SO$_2$ Removal

The SNRB^{TM} process can use either calcium- or sodium-based sorbents for SO$_2$ removal. During the 5-MWe demonstration, the calcium-based sorbents were commercial hydrated lime (Ca(OH)$_2$) and modified hydrated limes; sodium bicarbonate (NaHCO$_3$) was also evaluated.

Calcium-based sorbents: Upon injection into SO$_2$ laden flue gas, Ca(OH)$_2$ immediately reacts with SO$_2$ (Equation 1) and begins to dehydrate (Equation 2). The escaping water vapor creates internal pore passages, providing access for SO$_2$ diffusion into the interior of the Ca(OH)$_2$ particles. Equation 2 is much slower than Equation 1, and the reaction continues in the SNRB^{TM} baghouse. The product of dehydration, CaO, also reacts with SO$_2$ to give CaSO$_3$ (Equation 3), which in turn can oxidize to CaSO$_4$ (Equation 4).

$$Ca(OH)_2 + SO_2 \quad\quad \rightarrow CaSO_3 + H_2O \quad\quad\quad\quad\quad (1)$$
$$Ca(OH)_2 + heat \quad\quad \rightarrow CaO + H_2O \quad\quad\quad\quad\quad\quad (2)$$
$$CaO + SO_2 \quad\quad\quad\quad \rightarrow CaSO_3 \quad\quad\quad\quad\quad\quad\quad\quad (3)$$
$$CaSO_3 + \tfrac{1}{2}\,O_2 \quad\quad\quad \rightarrow CaSO_4 \quad\quad\quad\quad\quad\quad\quad\quad (4)$$

Reaction of the CO$_2$ in the flue gas with hydrated lime and CaO gives calcium carbonate, as shown in Equations 5 and 6:

$$Ca(OH)_2 + CO_2 \quad\quad \rightarrow CaCO_3 + H_2O \quad\quad\quad\quad\quad (5)$$
$$CaO + CO_2 \quad\quad\quad\quad \rightarrow CaCO_3 \quad\quad\quad\quad\quad\quad\quad\quad (6)$$

The carbonation reactions compete with the SO$_2$ removal reactions and are undesired because the CaCO$_3$ product will not react further with SO$_2$ under normal SNRB^{TM} operating conditions. In addition, the CaCO$_3$ may contribute to the formation of an outside product layer which hinders the reaction between SO$_2$ and the CaO/Ca(OH)$_2$ in the interior of the sorbent particle. The competing carbonation reaction appears to be the reason for the existence of an optimum sulfation reaction temperature range. Laboratory studies have shown that the carbonation reactions become dominant at temperatures above about 900ºF.

The sorbent also reacts with HCl present in the flue gas, as follows:

$$Ca(OH)_2 + 2HCl \quad\quad \rightarrow CaCl_2 + 2H_2O \quad\quad\quad\quad\quad (7)$$
$$CaO \quad + \; 2HCl \quad\quad\quad \rightarrow CaCl_2 + H_2O \quad\quad\quad\quad\quad\quad (8)$$
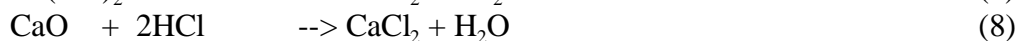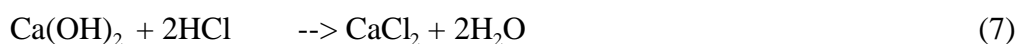
Removal of HCl from the flue gas reduces the potential for corrosion downstream of the baghouse and may also limit the formation of dioxins and furans. For coal-fired applications, HCl is a relatively

minor constituent of the flue gas.

Sodium-based sorbents: Using sodium bicarbonate as an example, the sulfur removal reactions are as follows:

$$2NaHCO_3 + SO_2 \quad \text{-->} \ Na_2SO_3 + H_2O + 2\,CO_2 \tag{9}$$
$$2NaHCO_3 + heat \quad \text{-->} \ Na_2CO_3 + H_2O + CO_2 \tag{10}$$
$$Na_2CO_3 + SO_2 \quad \text{-->} \ Na_2SO_3 + CO_2 \tag{11}$$
$$Na_2SO_3 + \tfrac{1}{2}\,O_2 \quad \text{-->} \ Na_2SO_4 \tag{12}$$
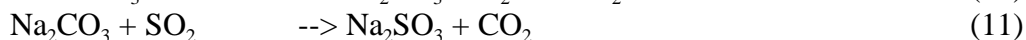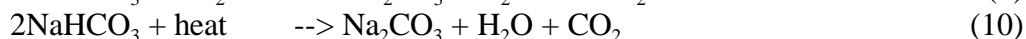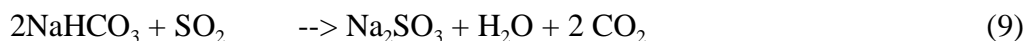
Below 300°F, $NaHCO_3$ immediately reacts with SO_2 to form sodium sulfite via Equation 9. At higher temperatures, $NaHCO_3$ decomposes to sodium carbonate before reacting with SO_2 (Equation 10). As water and CO_2 are given off, the sorbent particles' exposed surface area becomes available for reaction with SO_2 (Equation 11). While CO_2 is a product of the $NaHCO_3$ decomposition, the amount generated is minimal compared to that already present in the flue gas generated by coal combustion.

Other reactions competing for available sorbent include:

$$NaHCO_3 + HCl \quad \text{-->} \ NaCl + H_2O + CO_2 \tag{13}$$
$$Na_2CO_3 + 2HCl \quad \text{-->} 2NaCl + CO_2 + H_2O \tag{14}$$
$$NaHCO_3 + HF \quad \text{-->} \ NaF + H_2O + CO_2 \tag{15}$$

Sodium bicarbonate provides an order of magnitude higher removal efficiency for HCl than for SO_2, and has been successfully used for acid gas removal at waste-to-energy plants.

NO_x Removal

When the limits on NO_x emissions cannot be met by combustion controls such as low-NO_x burners (LNBs) and reburning, post-combustion treatment of the flue gas is required. A major post-combustion control method currently in use is SCR, which was chosen for incorporation in the SNRB™ process. A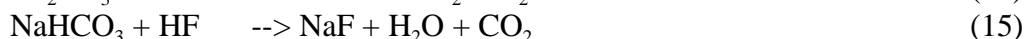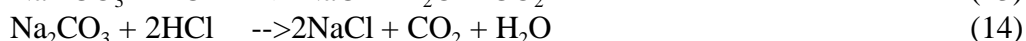n alternative post-combustion technology is selective noncatalytic reduction (SNCR). In SCR, NO_x in the flue gas reacts with NH_3 in the presence of a catalyst, giving water and nitrogen. In the presence of oxygen, ammonia reacts with NO and NO_2 as follows:

$$4NH_3 + 4NO + O_2 \quad \text{-->} \ 4N_2 + 6H_2O \tag{16}$$
$$4NH_3 + 2NO_2 + O_2 \quad \text{-->} \ 3N_2 + 6H_2O \tag{17}$$

SCR operates at an NH_3/NO_x stoichiometric ratio of 1.0. Side reactions include oxidation of SO_2 to SO_3, oxidation of NH_3 to NO_x, thermal decomposition of NH_3, and the creation of NO.

SNRB™, which operates at a high temperature (> 700°F), uses a nonpromoted zeolite catalyst for SCR. At temperatures below 700°F, promoted catalysts containing titanium oxide (TiO_2) or vanadium (V_2O_5) may be required to achieve high NO_x removal efficiency and maintain low NH_3 slip. Slip is defined as the concentration of NH_3 remaining in the gas stream after a post-combustion NO_x

reduction unit.

A side benefit of using sodium-based sorbents for SO_2 removal is the reduction of NO_x according to the following equations:

$$2NaHCO_3 + 2NO + \tfrac{1}{2} O_2 \rightarrow 2NaNO_2 + H_2O + 2CO_2 \qquad (18)$$
$$Na_2CO_3 + 2NO + \tfrac{1}{2} O_2 \rightarrow 2NaNO_2 + CO_2 \qquad (19)$$
$$NaNO_2 + \tfrac{1}{2} O_2 \rightarrow NaNO_3 \qquad (20)$$
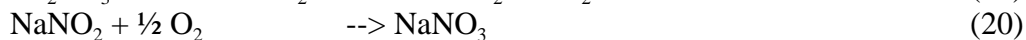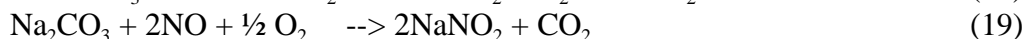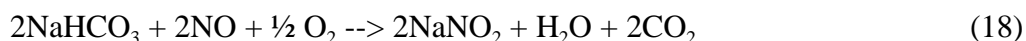
While the reaction mechanisms with NO_x are not fully understood, a relationship has been found between SO_2 removal and NO_x removal. One study showed that NO reacts with $NaCO_3$ or, at lower temperature, with $NaHCO_3$, but only in the presence of SO_2.   However, at temperatures above 575°F, $NaNO_2$ and $NaNO_3$ are not stable and decompose to NO_x. Therefore, with sodium injection, NO_x removal is achieved only at operating temperatures below 575°F.

Particulates Removal

Fabric filters allow the flue gas to pass, while retaining most of the particulates. When the fabric is new, the particles are initially deposited on the fibers. With progressive use, collection transfers to the developing filter cake. The device tested in this project was a pulse-jet fabric filter, in which the filter medium is in the form of a long bag supported on a metal cage. The gas to be cleaned flows through the bag from the outside, with particle collection on the outside of the bag. The pressure drop increases with time, requiring periodic removal of the filter cake. This is accomplished by introducing a pulse of compressed air into the interior of the bags, resulting in an abrupt increase in pressure and a momentary reversal in gas flow. With the bag fully expanded, the filter cake falls off the surface. Cleaning is achieved with the filter unit remaining "on-line," while the flue gas continues to flow through the bags.

Pulse-jet baghouses generally operate at higher air-to-cloth (ATC) ratios than other available fabric filters. Operation at higher ATC ratios can reduce the required filter surface area, resulting in reduced equipment size and capital cost. A disadvantage of pulse-jet technology is that the high impact cleaning may shorten bag life.

Two types of bag filters were tested in the demonstration project: (1) a woven ceramic design, made by 3M Company, called Nextel^{TM}, and (2) a glass fiber fabric, made by Owens-Corning, called S2-Glass. Preliminary testing showed these materials to be suitable for the proposed usage. The preliminary tests also included evaluation of a third material, an experimental calcium silicate filter prepared by Acurex, called Silontex. Silontex was found to be unacceptable because of poor cleaning characteristics, and therefore was not tested in the demonstration program.

Hot gas filtration in the SNRB^{TM} demonstration project was one of the first applications using filter fabrics upstream of the combustion air heater in the boiler cycle. Hot gas filtration offers advantages in energy savings and reduced erosion in the heat exchanger. However, the primary reason for its use in the SNRB^{TM} process is the need for high temperatures for SO_2 and NO_x removal. One disadvan-

tage of hot gas filtration is the higher bag cost relative to conventional fabrics. However, SNRB^{TM} is not limited to high temperatures. When using NaHCO$_3$ injection for SO$_2$ removal, the process can be conducted below 600ºF, permitting use of more conventional fabrics.

C.   Project Objectives/Results

The goal of this project was to demonstrate SNRB^{TM} retrofit technology for reducing SO$_2$, NO$_x$, and particulate emissions from coal-fired utility boilers. The project was designed to confirm pilot-scale results and to develop scaleup procedures necessary for commercial application of the technology, as well as to resolve those technical issues that could not be adequately addressed in an engineering study or in pilot-scale tests.

A specific objective was to demonstrate SO$_2$, NO$_x$ and particulate removal during extended operation with fully-integrated, commercial-sized components to meet the following performance targets:

•	Greater than 70% SO$_2$ removal with a calcium-based sorbent
•	Greater than 90% SO$_2$ removal with a sodium-based sorbent
•	Greater than 90% NO$_x$ removal with minimal ammonia slip
•	Compliance with the NSPS for particulate emissions from coal-fired boilers of 0.03 lb/10^6 Btu

All of the performance targets were met or exceeded during the test program. SO$_2$ removal efficiency was greater than 80% when using commercial hydrated lime at a Ca/S molar ratio between 1.8 and 2.0 and an operating temperature of about 830ºF. With NaHCO$_3$ injection, 84% SO$_2$ removal was achieved at an Na/S ratio of 1.0 and a baghouse temperature of 450ºF, corresponding to a sorbent utilization of 85%. Greater than 90% removal was achieved at higher Na/S ratios, with reduced sorbent utilization.

NO$_x$ removal greater than 90% with ammonia slip less than 5 ppm was achieved over catalyst temperatures ranging from 700 to 900ºF, at an NH$_3$/NO$_x$ stoichiometric ratio of 0.9. Particulate emissions downstream of the baghouse averaged 0.018 lb/10^6 Btu, corresponding to a collection efficiency of 99.9%.

The demonstration facility was operated for about 2300 hours, including more than 25 cold startup cycles. No degradation of catalyst or filter bags was observed. In three periods of planned continuous operation for more than 200 hours each, system availability averaged 99%.

D.   Environmental Performance

Commercial deployment of SNRB^{TM} would offer a means of significantly reducing SO$_2$, NO$_x$ and particulate emissions, thereby benefiting the environment. Utilization of the by-product solids, discussed subsequently, would have a beneficial impact because the amount of waste to be disposed of would be reduced. However, this capability was not demonstrated in the test program.

E.   Post-Demonstration Achievements

The major activity since completion of the demonstration project has been the development of a marketing strategy, as discussed in subsequent sections. There have been no process developments since completion of the demonstration program.

III   Operating Capabilities Demonstrated

A.   Size of Unit Demonstrated

The demonstration project was conducted at Ohio Edison's R.E. Burger Plant, using a slipstream of flue gas from Boiler No. 8, which is a 160-MWe wall-fired boiler. The slipstream was equivalent to about 5 MWe of power generation. Although this is a relatively small capacity, the fabric filters used in the baghouse were representative of full-scale commercial modules. The chemical principles involved in NO_x reduction and SO_2 absorption are independent of plant size. Thus, the results of this demonstration project should be applicable to any member of the boiler population.

Over the period of the demonstration project, the boiler was fired with seven Midwestern bituminous coals having a sulfur content ranging from 2.2 to 5.1%, averaging about 3.5%. Typical coal properties are given in Table 1.

B.   Performance Level Demonstrated

SO_2 Emissions Reduction

At a baghouse operating temperature of 830°F and higher, use of a commercial hydrated lime sorbent at a Ca/S molar ratio of 1.8 or above resulted in over 80% SO_2 removal, with 40-45% calcium utilization. This represents significantly improved performance compared with the 60% removal at 30% utilization typical of other dry calcium-based sorbent injection processes.

For sodium-based sorbents, two moles of sorbent are required per mole of SO_2 removed. This leads to the use of the term normal stoichiometric ratio (NSR), which is defined as the ratio of the moles of Na injected to the moles of SO_2 in the flue gas, divided by 2. Thus, an Na/S ratio of 2.0 is equivalent to an NSR of 1.0. In the test program, sodium-based sorbents provided over 90% removal efficiency, with sorbent utilization of 85%, at an NSR of 1.0. Use of sodium-based sorbents permits operation at a substantially reduced baghouse temperature of about 450°F.

NO_x Emissions Reduction

NO_x emissions were reduced by 90%, to less than 0.10 lb/10^6 Btu, with NH_3 slip limited to less than 5 ppm. This performance was insensitive to temperature and space velocity. NO_x reduction varied from 50 to 95% over an NH_3/NO_x ratio ranging from 0.5 to 0.9. No appreciable physical degradation or loss in catalyst activity was observed over the duration of the test program.

Particulates Emissions Reduction

Particulate emissions were controlled to well below the NSPS level of 0.03 lb/10^6 Btu throughout the test program, averaging about 0.018 lb/10^6 Btu. This represents a particulate removal efficiency of 99.9%. Efficiency was independent of air-to-cloth ratio, sorbent injection rate, baghouse pressure

drop, and bag cleaning frequency. There was no difference in efficiency with and without the SCR catalyst installed in the baghouse.

Other Emissions

Greater than 96% HCl removal and 84% HF removal were achieved when using hydrated lime sorbent. Removal efficiencies for hazardous air pollutants (HAPs) exceeded 95%, with the exception of mercury. HAPs emissions were not measured when $NaHCO_3$ sorbent was used.

C.   Major Operating and Design Variables Studied

With several functions taking place simultaneously, optimizing the SNRB™ process was technically challenging. Studies of the individual variables are summarized in the following paragraphs.

SO_2 Removal -- Calcium-Based Sorbents

•   **Effect of Calcium/Sulfur Ratio** The effects of reagent ratio on SO_2 removal and calcium utilization are shown in Figure 3. SO_2 removal increases with increasing Ca/S ratio, reaching about 90% at a 1.8 Ca/S ratio. Calcium utilization is also 90%. Baghouse temperature ranged from 830 to 860°F in these tests.

•   **Effect of Sorbent Injection Temperature and Residence Time** The demonstration unit was equipped with five sorbent injection locations, which were used to study the effects of sorbent injection temperature and residence time. The injection temperature in the duct ahead of the baghouse was varied by means of a propane-fired burner. Over the range of 1000-1200°F, SO_2 removal decreased with increasing injection temperature. This effect, which is shown in Figure 4, is likely due to sintering of the lime particles, which is known to decrease reactivity. Over the range of 2 to 4 seconds residence time in the duct, no significant effect on SO_2 removal was observed. These findings are consistent with the observation that the majority of the SO_2 removal takes place in the baghouse. Consequently, it was determined that the optimum sorbent injection point is at the baghouse inlet, and that preheating sorbent in the duct is not beneficial.

•   **Effect of Baghouse Temperature** The baghouse operating temperature has a significant effect on SO_2 removal, as shown in Figure 5. The results suggest an optimum baghouse operating temperature between 800 and 860°F with hydrated lime sorbent.

•   **Effect of Alternative Sorbents** Modified lime hydrates were evaluated as a means of enhancing SO_2 removal and lime utilization. Improved SO_2 removal has been attributed to the finer mean particle size and increased porosity of the modified hydrates. Based on the results of bench-scale screening studies, sugar hydrated lime (SHL) and calcium lignosulfated lime (CLS) were evaluated in the demonstration project. The results, given in Figure 6, show over 90% SO_2 removal with SHL at a Ca/S ratio of 2.0, and slightly lower SO_2 removal with

CLS at the same conditions. For comparison, commercial hydrated lime sorbent gave about 85% SO_2 removal at the same conditions.

- **Effect of Air/Cloth Ratio** SO_2 removal efficiency was not affected by ATC ratio over a range of 3.0-4.5 $acfm/ft^2$.

- **Effect of SO_2 Concentration** One of the premises of the $SNRB^{TM}$ process is that SO_2 removal is enhanced by reducing sorbent particle size, thereby increasing surface area. This is based on the assumption that the CaO/SO_2 reaction is limited by diffusion of the gas through the layer of $CaSO_3$ and $CaSO_4$ surrounding the particles. Therefore, initial SO_2 concentration would be expected to have a direct effect on reaction rate. However, over the relatively narrow range of SO_2 concentrations evaluated, no effect was observed. This effect could not be fully investigated since, for a given coal feed, it was not feasible to vary the inlet SO_2 concentration beyond normal variations in boiler operation.

- **Effect of Injector Diameter** Injector diameter influences sorbent injection velocity, which in turn presumably could affect performance. This was investigated, but over the limited range of velocities tested there was no significant effect on SO_2 removal.

- **Effect of Bag Cleaning** Since the reaction of SO_2 with the sorbent begins in the flue duct and continues in the baghouse, removing the filter cake from the bags should affect SO_2 removal. As the quantity of filter cake on the bags increases, the amount of unreacted sorbent available for reaction increases. SO_2 removal efficiency increases with time until the bags are cleaned, at which point the efficiency decreases due to removal of solids from the surface of the bags. Removal efficiency varied about 5% over the cleaning cycle.

SO_2 Removal -- Sodium-Based Sorbents

The sodium-based sorbent tested in this project, $NaHCO_3$, provided greater sorbent utilization than hydrated lime. In addition, as discussed previously, $NaHCO_3$ reacts with NO_x. Over 90% SO_2 removal and 25% NO_x reduction were achieved with $NaHCO_3$ injection followed by parti-culate collection in the baghouse. The test program showed the following results:

- **Effect of Sodium/Sulfur Stoichiometric Ratio** Test results demonstrated 84% SO_2 removal at an NSR of 1.0, with a sorbent utilization of 85%. At an NSR of 0.5, SO_2 removal was about 52%, with sorbent utilization of 100%.

- **Effect of Baghouse Temperature** Sodium-based sorbents are effective at relatively low baghouse temperatures. At an NSR of 2.0, greater than 96% SO_2 removal was achieved at temperatures as low as 425ºF, decreasing slightly as the temperature was increased to 850ºF. At a more cost effective NSR of 1.0, SO_2 removal decreased from over 80% at 450ºF to about 70% at 625ºF. Operating at temperatures even lower than 450ºF is expected to provide increased sorbent utilization, but equipment limitations precluded testing this concept.

NO$_x$ Removal -- The variables reported below were evaluated while operating the SNRB^{TM} demonstration unit with calcium-based sorbents for SO$_2$ removal.

- **Effect of Temperature** As anticipated, the zeolite catalyst provided uniform NO$_x$ reduction performance over a wide temperature range, 700-865°F.

- **Effect of Space Velocity** The design space velocity was 3300/hr at a baghouse ATC ratio of 4.0 acfm/ft^2 and an operating temperature of 800°F. There was little variation in performance over a space velocity range of 2100 to 3400/hr.

- **Effect of NH$_3$/NO$_x$ Ratio** The NH$_3$/NO$_x$ ratio was found to have the greatest impact on NO$_x$ removal. Figure 7 shows that an NH$_3$/NO$_x$ ratio of 0.85 provided 90% NO$_x$ reduction at a baghouse temperature in the range of 790 to 865°F.

- **Effect of Boiler Fluctuations** There was a slight increase in NO$_x$ removal with reduction in boiler load. This phenomenon did not seem to be a result of the drop in space velocity or temperature. Rather, it appeared to result from the relatively slow response of the NH$_3$/NO$_x$ ratio control system to rapid changes in baghouse inlet NO$_x$ concentration, which led to over-ramping. The highly porous zeolite catalyst also may serve as a NH$_3$ reservoir.

- **Effect of O$_2$ Content** Over the range of 4-7% O$_2$ in the flue gas, NO$_x$ removal remained essentially constant.

- **Effect of SO$_2$ Content** SO$_2$ concentration at the SCR reactor inlet was varied in a series of tests. As SO$_2$ increased from 300-850 ppm, NO$_x$ removal decreased by 7 percentage points.

- **Effect of Bag Cleaning** NO$_x$ removal efficiency varied somewhat during the cleaning cycle. Periodic removal of the filter cake temporarily reduces the flow resistance in the module being cleaned, resulting in increased gas flow through the bags. The short-term decline in NO$_x$ reduction may be attributed to the removal of active fly ash from the surface of the filter bags.

Particulates Removal

Both the Nextel^{TM} and the S2-Glass fabric filters exhibited desirable performance characteristics and are suitable for commercial operation. The other filter fabric, Silontex, proved unsuitable for pulse-jet baghouse operation because of cleaning difficulties. For the Nextel^{TM} and S2-Glass fabric filters, satisfactory operation was achieved with a cleaning cycle of 45 minutes at an ATC ratio of 3.7 acfm/ft^2. Under these conditions, the pressure drop across the filter was about 12 inches of water.

Parasitic power requirements for SNRB^{TM} include the power required to operate the fans, which in turn is a function of the fabric filter pressure drop. At the design pressure drop of 12 inches of water, the power consumption represents about 6% of the total operating cost.

The high temperature conditions in the baghouse might be expected to have a detrimental effect on fabric life. However, extensive testing in a separate facility simulating baghouse operation showed the Nextel™, S2-Glass, and Silontex fabric filters to be quite durable. Over a period of 3700 hours, the fabric filters were subjected to 11,200 cleaning pulses at temperatures ranging from 600°F to 720°F, with only minor damage noted. According to B&W, these data indicate economically acceptable bag life. On the basis of cake release characteristics and pressure drop studies, the S2-Glass fabric was selected for use in the SNRB™ process.

The results of parametric studies on baghouse performance are summarized as follows:

- The presence of SCR catalyst in the baghouse had no effect on particulate collection efficiency.

- On-line cleaning with a pulse air pressure of 30-40 psi was sufficient for cleaning the bag/catalyst assemblies.

- Filter fabric performance was relatively insensitive to boiler operation and sorbent injection.

D.   Boiler Impacts

The SNRB™ demonstration project had no effect on boiler performance, since it involved only post-combustion treatment of a flue gas slipstream.

E.   Commercialization of the Technology

Current Status

No commercial installations of SNRB™ have been made to date. B&W states its intention to commercialize the technology in view of the success achieved in the demonstration program and a desire to recover its investment in the development. Our assessment is that this is a niche technology, with limited applications in the United States at present since compliance with SO_2 emissions regulations is currently being met through fuel switching, trading of allowances, and conventional FGD. For NO_x emissions reduction alone to meet CAAA Title IV emissions standards, LNBs are the technology of choice. Higher levels of NO_x emissions reduction, such as required under CAAA Title I, are achieved with SCR.

For international applications, B&W states its intention to involve local partners and/or third party funding for engineering, material supply, and erection of SNRB™ systems. As the developer of SNRB™, B&W retains all rights to use of the technology. B&W would consider licensing the technology under appropriate circumstances.

Future Work

This project demonstrated the components of SNRB™ at commercial scale. In practice, the SNRB™ process is expected to provide improved overall heat transfer efficiency of the boiler system and reduced net plant heat rate by recovering additional energy from the hot, clean flue gas following the baghouse. However, because the 5-MWe demonstration program used a slipstream from the boiler flue gas, this potential benefit of the technology could not be fully investigated. B&W's reported economic projections do not include a credit for heat recovery improvement.

As indicated previously, an advantage of the SNRB™ process is the fact that corrosion potential is reduced because SO_2 removal occurs upstream of the air heater. The demonstration project included a limited amount of corrosion testing, focusing on potential acid gas condensation in equipment downstream of the air heater. This was accomplished by means of a probe, made of multiple hollow cylindrical segments of several grades of steel, inserted into the flue gas downstream of the air heater. Visual observation of these specimens showed significant corrosion if the flue gas temperature is allowed to fall below about 250°F. There is a need for long-term corrosion testing to explore this problem more fully.

Retrofit applications may require additional heat transfer surface to provide higher heat recovery and hence improved overall thermal efficiency. Although the SNRB™ system permits operating at lower temperatures than furnace sorbent injection, a hotter flue gas exit temperature is required for maximum NO_x and SO_2 removal.

The by-product solids from SNRB™ are high in calcium and have some pozzolanic properties which make them potentially desirable for soil conditioning and construction material applications. The SNRB™ solids, which are alkaline, could be used to offset the low pH of ash generated by other boilers at the same plant site. Future work could include developing these applications. If appropriate outlets are not found, the solids must be disposed of by landfilling. Solids from the demonstration facility were successfully disposed of in a landfill without special pretreatment or handling.

Leachate tests were performed on the solid by-products from both the calcium and sodium-based sorbent injection studies. For both types of sorbent, the concentrations of metals regulated by the Resource Conservation Recovery Act (RCRA) were found to be below primary drinking water standards.

IV   Market Analysis

A.   Potential Markets

The SNRB^{TM} process is potentially applicable to all types of conventional coal-fired boilers including stoker, cyclone, wall-fired and tangentially-fired boilers. Fluidized bed boilers would not be a likely application. Major advantages of SNRB^{TM} are the relatively low space requirements and the use of a single processing unit when both SO_2 and NO_x removal are required. The excellent particulate removal capability of SNRB^{TM} may offer further benefits, especially in the light of increasingly stringent air quality regulations.

Although SNRB^{TM} is potentially applicable to any boiler size, smaller boiler sizes are favored from the standpoint of economic competitiveness. In applications involving boilers producing high levels of NO_x, it might be advantageous to use LNBs in conjunction with SNRB^{TM}, thereby reducing the catalyst requirements and minimizing baghouse pressure drop.

In the U.S., relatively few of the plants regulated under Phase I of the 1990 CAAA have installed scrubbers for SO_2 control. A large proportion of these plants have achieved compliance by fuel switching or by purchasing SO_2 emission credits. However, since prices for SO_2 allowances are increasing, a market for FGD is likely to develop in Phase II. The SNRB^{TM} process will be applicable primarily in situations where less than 90% SO_2 removal is required.

According to B&W, a key initial market for the SNRB^{TM} technology will consist of retrofits to existing boilers with generating capacities of 100 to 200 MWe. Units of this size represent 65% of the total U.S. coal-fired boiler population without SO_2 emission control through Phase I of the CAAA. This represents a total market of about 15,000 to 20,000 MWe.

Currently, many small industrial boilers rely on the use of natural gas, thus avoiding the need for pollution control systems. If gas becomes less available and/or more expensive, the economics would change and coal could become the fuel of choice, providing new opportunities for SNRB^{TM}. There are currently 2400 MWe of small, industrial gas-fired boilers installed annually in the U.S. If 10% of these new sales were to switch to coal, the potential market for SNRB^{TM} would be about 240 MWe. A large international power market is also developing, representing additional opportunities for SNRB^{TM}.

B.   Economic Assessment of Utility Boiler Applications

SNRB^{TM} Costs

The B&W Final Report includes an economic estimate for a 150-MWe retrofit unit, using a projected process design for the nth plant which incorporates improvements based on experience gained from the 5-MWe demonstration and other commercial installations. For an assumed 85% reduction in SO_2 emissions and 90% reduction in NO_x emissions, the estimated capital cost is $253/kW. For a 15-year

project life, the levelized cost on a current dollar basis is 15.8 mills/ kWh. This is equivalent to $721/ton of $SO_2 + NO_x$ removed. On a constant dollar basis, the levelized cost is 12.1 mills/kWh, equivalent to $553/ton of $SO_2 + NO_x$ removed. These economics are reported in 1994 dollars and are given in more detail in Table 2.

Hydrated lime is used as the SO_2 sorbent, at a Ca/S molar ratio of 1.8 based on the SO_2 content of the flue gas. The design ATC ratio in the baghouse is 4.0 acfm/ft^2, and the baghouse operates at 850°F.

The economics assume installation of a new pulse-jet fabric filter, replacing the existing particulate emissions control equipment at the plant. The costs also include the SCR catalyst, the high-temperature fabric filter bags, sorbent and ammonia storage and injection systems, provisions for potential upgrades to the induced draft fan, a new combustion air heater, and modification of the existing fly ash handling equipment to accommodate the increased volume of solids. The addition of auxiliary heat transfer surface is not included.

The economics assume a 5-year life for the SCR catalyst and filter bag replacement every 3 years. These assumptions seem to be consistent with currently available data. The cost of disposal of the by-product solids is included in the economics. The economics would be improved if value were realized for these by-products, thereby also reducing disposal costs. No provision is made for recovery of additional heat from the cleaned flue gas.

The economics assume a credit of $130/ton for SO_2 emission allowances in the year 2000, which is probably a realistic figure. No credit is taken for reducing NO_x emissions, since allowance trading for this pollutant is not widespread.

As mentioned previously, SNRB^{TM} could be used as a polishing NO_x reduction process in conjunction with combustion modifications such as low-NO_x burners. Both ammonia consumption and SNRB^{TM} system pressure drop would be reduced as a result of the lower inlet NO_x concentration. The two systems could be optimized to achieve NO_x reduction at the lowest cost over a wide range of boiler operating conditions and fuel characteristics.

New plant costs could be lower than those for retrofit installations because modifications to existing boiler auxiliary systems and flue work would be eliminated.

Comparison with Other Technologies

B&W compared SNRB^{TM} economics with those for a combination of conventional technologies designed to achieve comparable emissions control [5]. SNRB^{TM} has lower capital (20% reduction) and levelized costs than a dry lime scrubber/SCR/fabric filter combination for a 100-MWe plant burning 1.5% sulfur coal.

V   Conclusions

The SNRB^{TM} test program demonstrated the feasibility of controlling multiple emissions from a coal-fired boiler in a single processing unit. The degree of emissions removals for SO_2, NO_x, and particulates all exceeded the project goals. A high degree of removal for HAPs was also achieved. The SNRB^{TM} system offers low space requirements, control of multiple pollutants, and operating flexibility. The pneumatic SO_2 sorbent and ammonia injection systems are expected to have high reliability because of their mechanical simplicity.

Despite these advantages, the SNRB^{TM} process may not be an economic choice for applications involving SO_2 removals above about 85%. For lower levels of SO_2 removal, the projected economics for SNRB^{TM} appear to be more favorable than those of existing processes which involve separate units for the same degree of control for SO_2, NO_x, and particulates.

Specific findings are summarized as follows:

• SO_2 removal of 85-90% was achieved at a calcium utilization of 40-45%, representing a significant improvement in performance over other dry lime injection processes.

• When firing 3-4% sulfur coal, compliance with the 1990 CAAA Phase I SO_2 emissions limit of 2.5 lb/10^6 Btu was achieved with a Ca/S molar ratio of less than 1.0. For the Phase II SO_2 emissions limit of 1.2 lb/10^6 Btu, compliance was achieved with a Ca/S molar ratio as low as 1.5. Phase II compliance is the more relevant emissions limit.

• When using $NaHCO_3$ as the sorbent, the Phase II SO_2 emissions limit was achieved at a Na_2/S molar ratio of less than 2.0 (NSR < 1.0).

• Compliance with the Phase I NO_x emissions limit of 0.45 lb/10^6 Btu for Group 1 boilers was achieved at an NH_3/NO_x ratio of 0.85, with an ammonia slip of 5 ppm or less.

• Particulate collection efficiency averaged 99.9%, corresponding to an average emissions rate of 0.018 lb/10^6 Btu. This is significantly lower than the NSPS value of 0.03 lb/10^6 Btu.

The high-temperature baghouse design incorporating an SCR catalyst for NO_x reduction was demonstrated successfully. The technology is ready for commercial application. The key feature of the technology is control of SO_2, NO_x, and particulates in a single process unit. However, this limits its commercial market to applications requiring control of all three components. Also, although the testing demonstrated greater than 90% SO_2 capture, this was achieved at high sorbent/sulfur ratios. For applications requiring a high percentage of sulfur removal, a modern conventional FGD unit with LNBs for NO_x control may be the preferred option.

VI   References

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8.   R. Martinelli, J.B. Doyle, and K.E. Redinger (Babcock & Wilcox), "SO_x-NO_x-Rox Box^{TM} Technology Review and Global Commercial Opportunities," Fourth Annual Clean Coal Technology Conference, Denver, Colorado, September 1995.

Abbreviations

ATC	Air-to-cloth (ratios)
B&W	Back and Wilcox Company
CAAA	Clean Air Act Amendments
CCT	Clean Coal Technology Program
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
FGD	Flue gas desulfurization
HAP	Hazardous air pollutants
NSPS	New Source Performance Standards
SCR	Selective Catalytic Reduction
SNRB	SO_x-NO_x-Rox Box^{TM}

Table 1. Typical Coal Properties

Coal Source   Midwestern bituminous

Proximate Analysis, wt% (as received)
  Fixed Carbon   45.78
  Volatile Matter   38.12
  Moisture   5.16
  Ash   10.94
  Total   100.00

Higher Heating Value, Btu/lb
  Wet   11,715
  Dry   12,352

Higher Heating Value, MJ/kg
  Wet   27.3
  Dry   29.8

Ultimate Analysis, wt% (dry)
  Carbon   72.06
  Hydrogen   5.04
  Sulfur   3.72
  Chlorine   0.04
  Oxygen   6.28
  Nitrogen   1.32
  Ash   11.54
  Total   100.00

Table 2. Summary of Performance and Cost Data

1994 Dollars

Coal Properties	Units	Value
Higher heating value (HHV)	Btu/lb	12,625
Power Plant Attributes With Controls		
Plant capacity, net	MWe	150
Power produced, net	10^9 kWh/yr	0.85
Capacity factor	%	65
Coal fed	10^6 tons/yr	0.33
SO_2 Emissions Control Data		
Removal efficiency	%	85
Emissions without controls	lb/10^6 Btu	4.31
Emissions with controls	lb/10^6 Btu	0.64
Amount removed	tons/yr	14,935
NO_x Emissions Control Data		
Removal efficiency	%	90
Emissions without controls	lb/10^6 Btu	1.02
Emissions with controls	lb/10^6 Btu	0.10
Amount removed	tons/yr	3,730
Total Capital Requirement	$/kW	253

	Levelization Factor[a]	mills/ kWh	$/ton SO_2 + NO_x Removed
Levelized Cost, Current $			
Capital charge	0.160	7.12	326
Fixed O&M	1.314	3.15	144
Variable O&M	1.314	5.48	251
Total		15.75	721
Levelized Cost, Constant $			
Capital charge	0.124	5.52	252
Fixed O&M	1.000	2.40	110
Variable O&M	1.000	4.17	191
Total		12.09	553

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a   Levelization based on 15-year project life, 38% tax rate, 4% inflation, and the following capital structure: 50% debt @ 8.5% return, 15% preferred stock @ 7.0% return, and 35% common stock @ 7.5% return, giving a weighted cost of capital of 7.925% (including inflation).
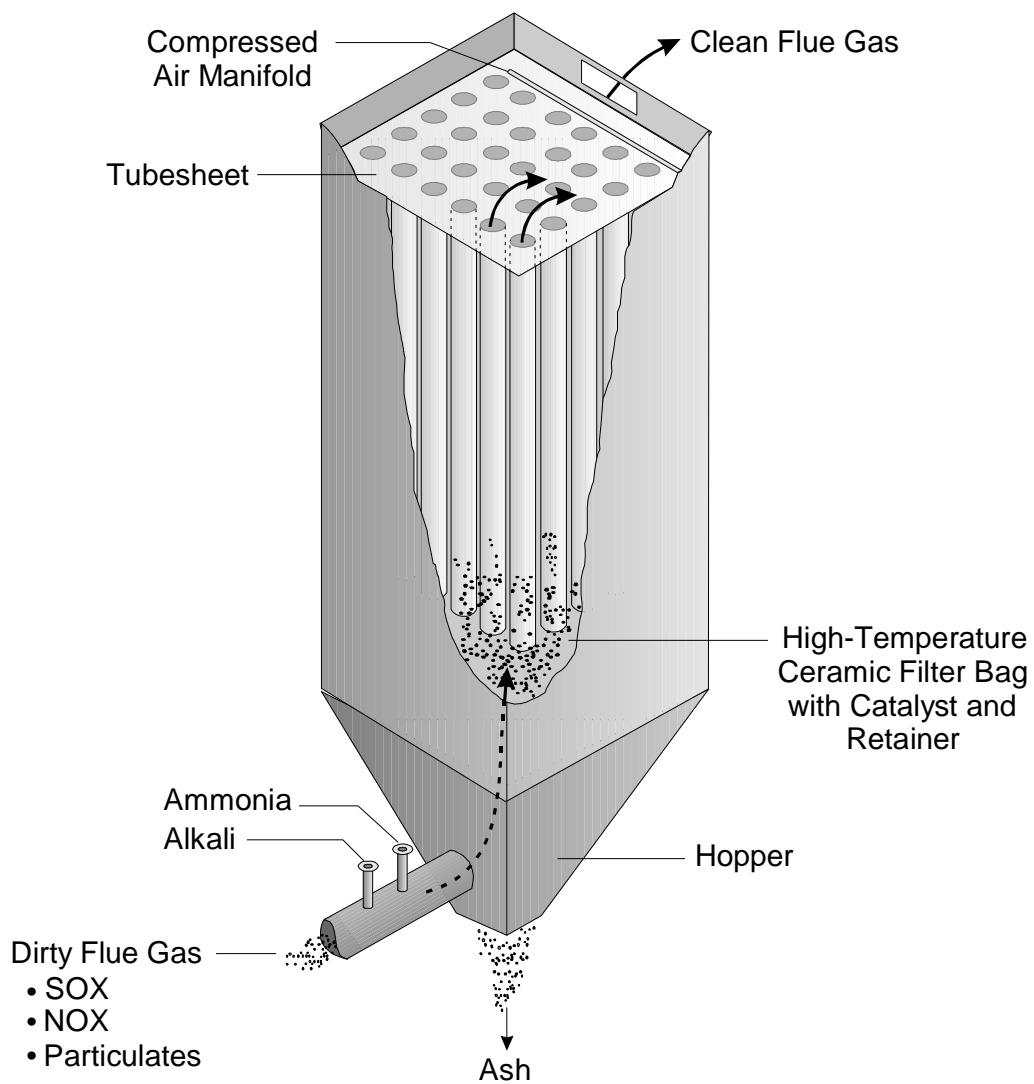
Compressed Air Manifold

Clean Flue Gas

Tubesheet

High-Temperature Ceramic Filter Bag with Catalyst and Retainer

Ammonia

Alkali

Hopper

Dirty Flue Gas
• SOX
• NOX
• Particulates

Ash

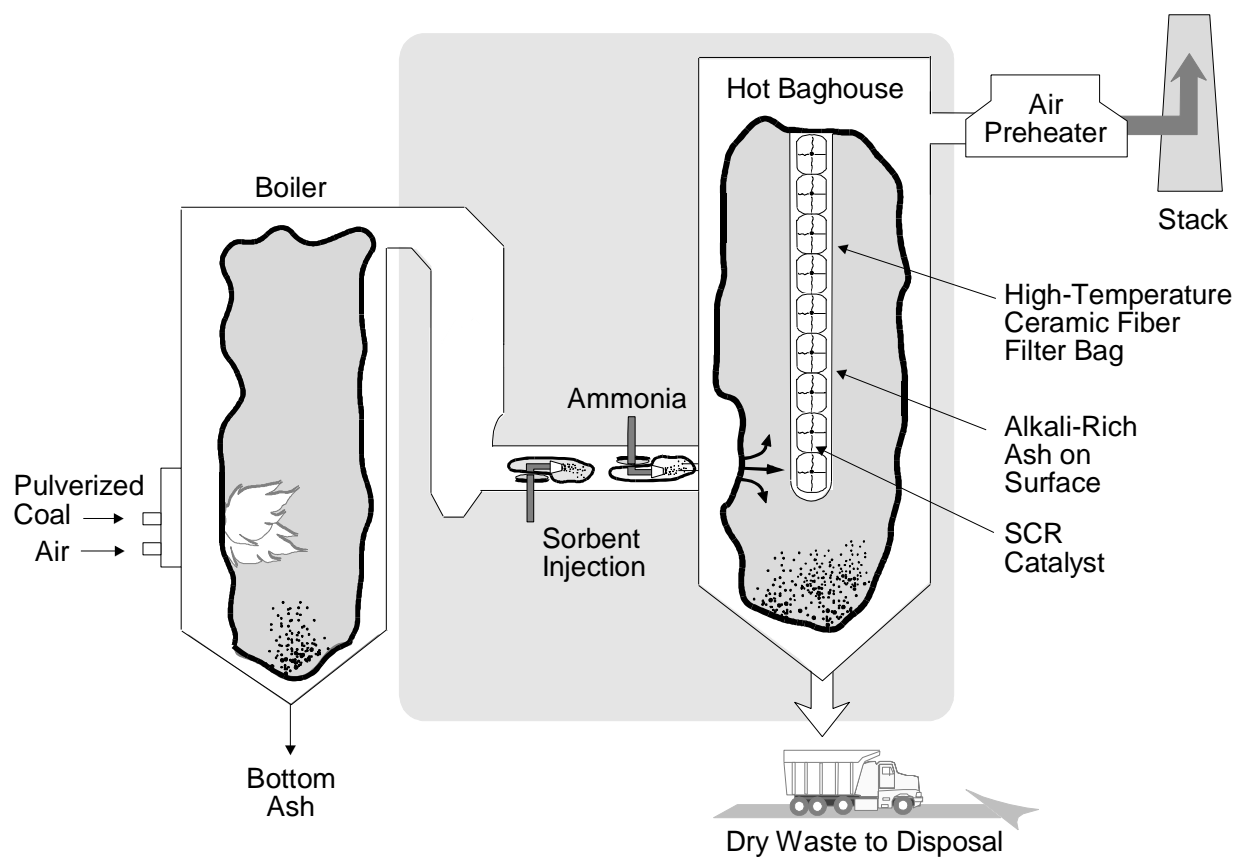**Figure 1. SNRB™ Baghouse Schematic**
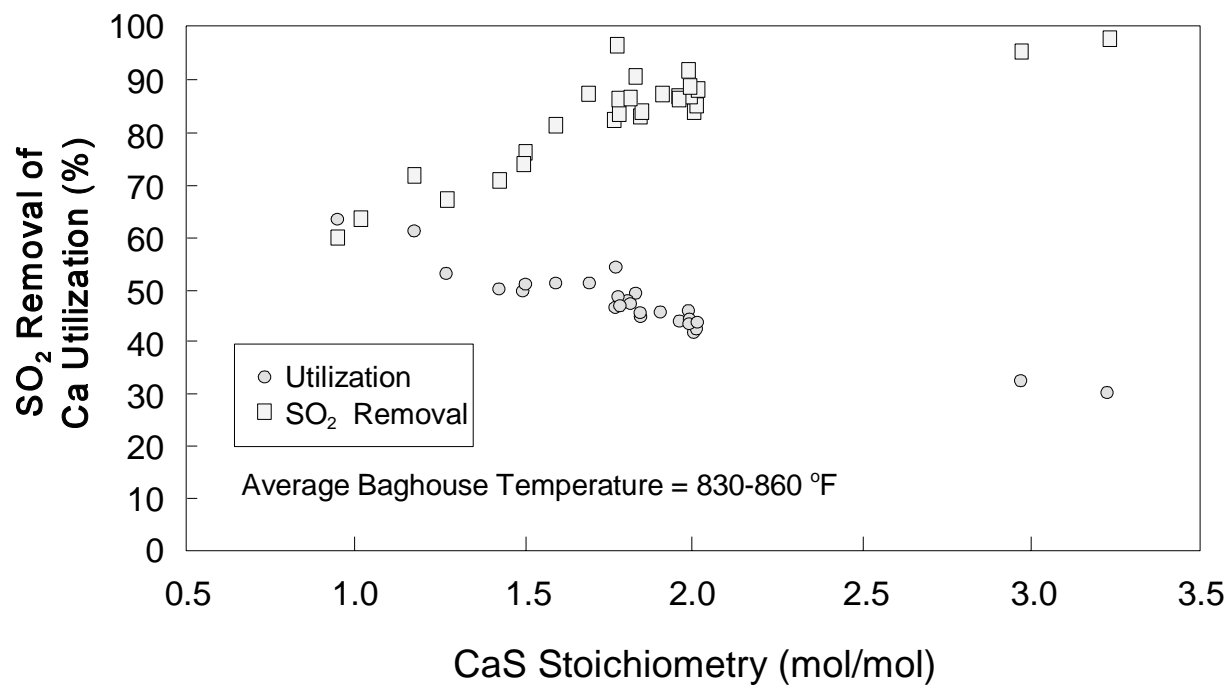
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Figure 2. SNRB™ System Integration

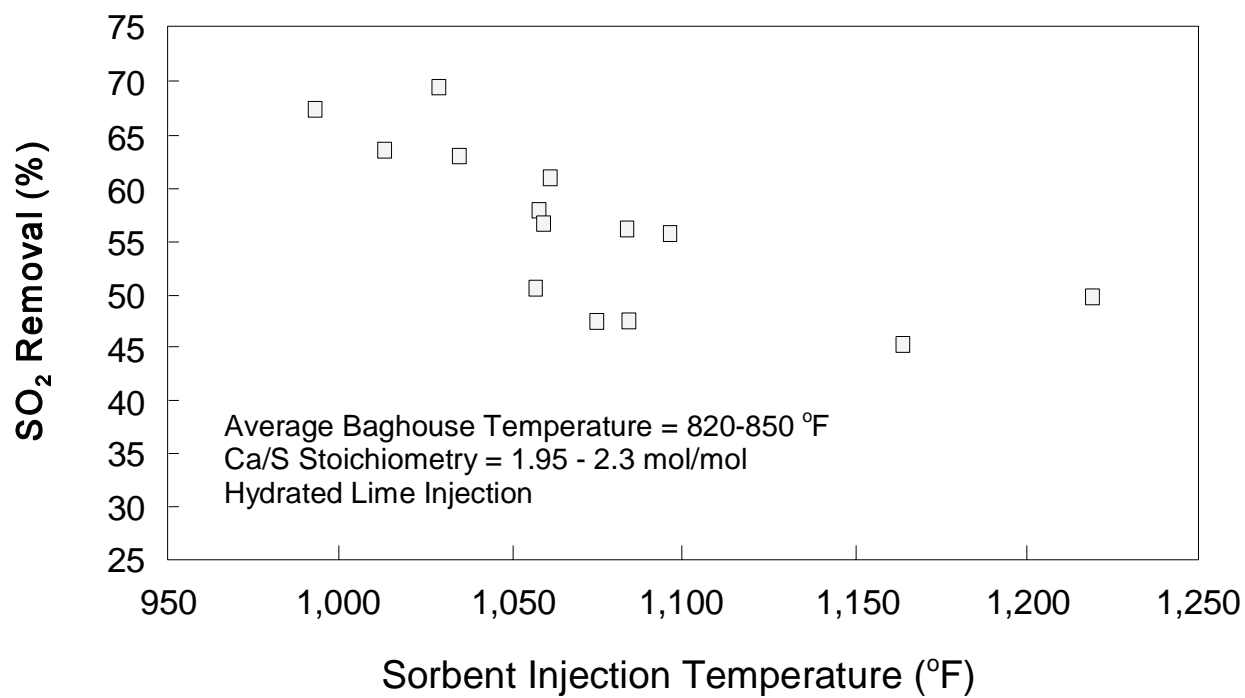**Figure 3. Effect of Ca/S Stoichiometry on SO$_2$ Removal and Ca Utilization**

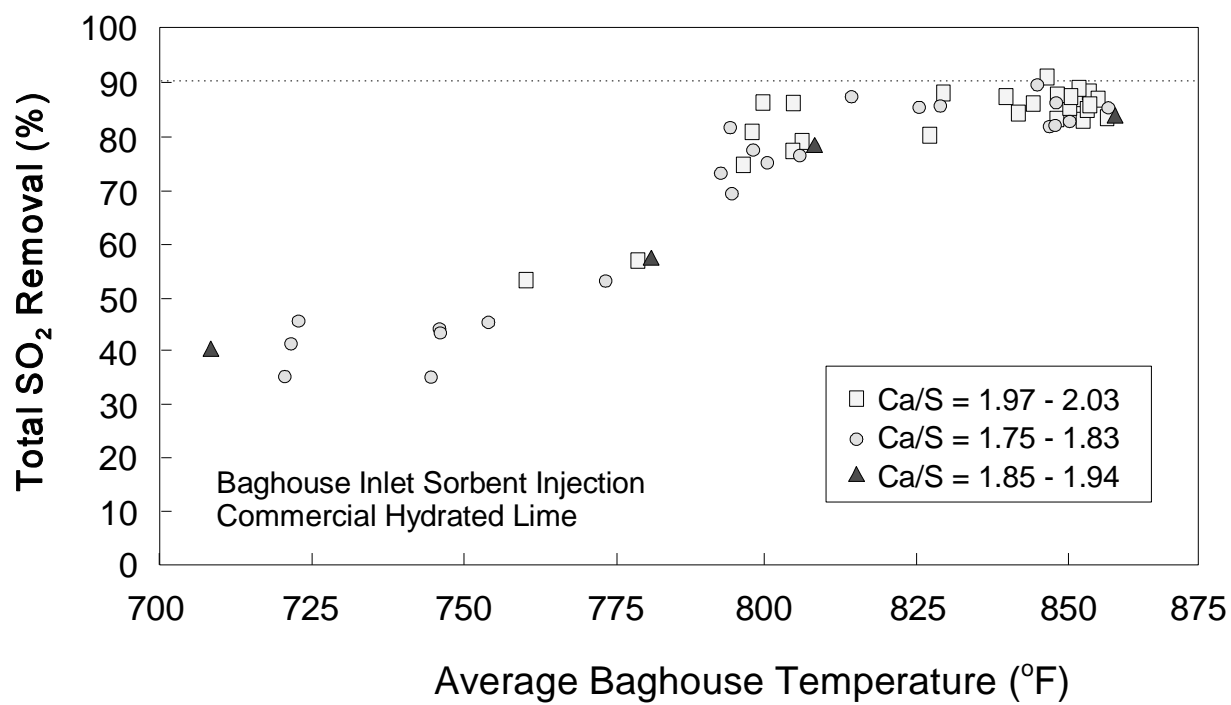**Figure 4. Effect of Sorbent Injection Temperature on SO₂ Removal**

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Figure 5. Effect of Baghouse Temperature on SO$_2$ Removal at Ca/S Ratios of 1.7 to 1.9
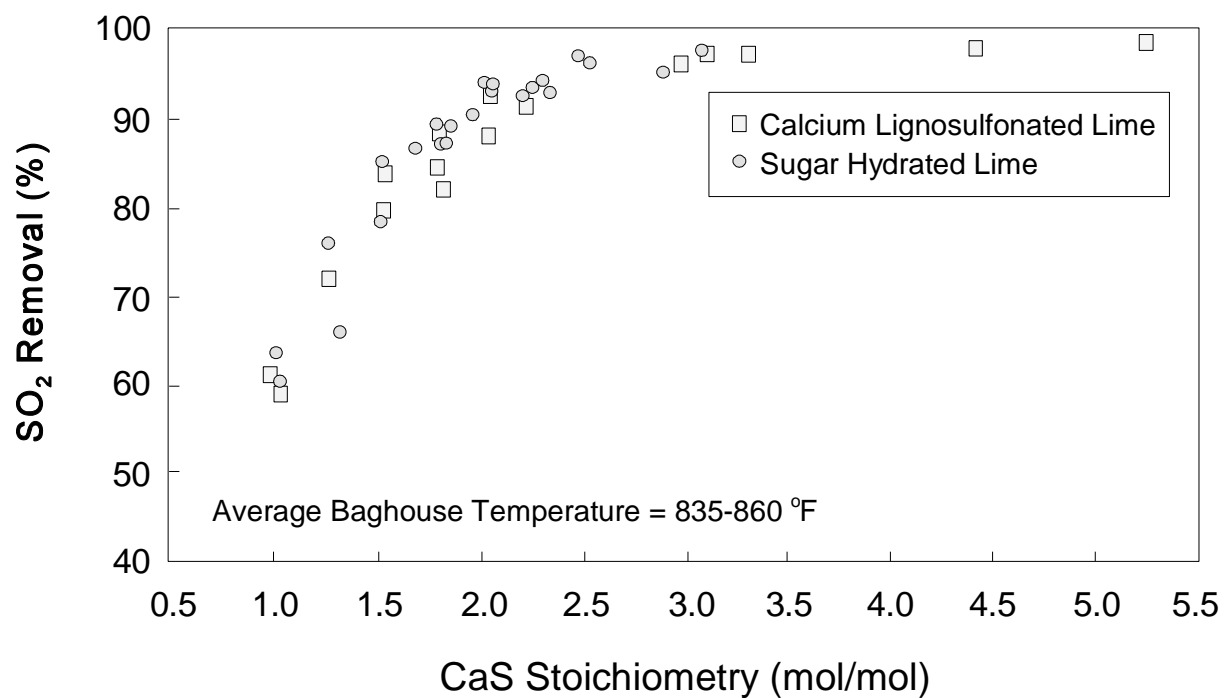
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Figure 6. Effect of Modified Hydrate Ca/S Ratio on SO₂ Removal
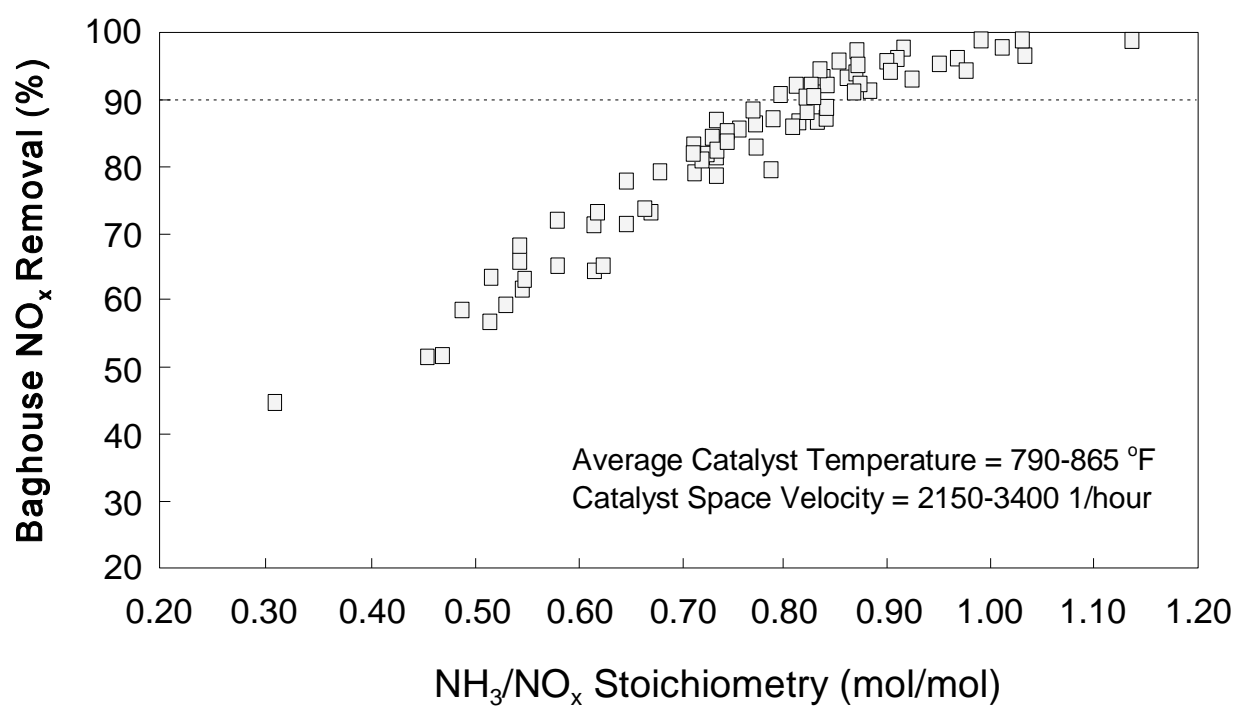
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Figure 7. Effect of NH$_3$/NO$_x$ Ratio on NO$_x$ Removal

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